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A recommendation on standardized surface resistance for hourly calculation of reference ET_o by the FAO56 Penman-Monteith method

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Abstract

Continued development of networks of electronic weather stations worldwide has increased the availability of weather data for calculating ET_o on an hourly basis. There has been question and debate as well as studies on the appropriate expression and parameterization for the surface resistance (r_s) parameter of the Penman-Monteith (PM) equation and the associated coefficient for the reduced form FAO-PM equation when applied hourly. This paper reviews the performance of the FAO-PM method using $r_s = 70\ \mathrm{s\ m^{-1}}$ for hourly periods and using a lower $r_s = 50\ \mathrm{s\ m^{-1}}$ value during daytime and $r_s = 200\ \mathrm{s\ m^{-1}}$ during nighttime. Variability in hour to hour trends in r_s among locations and dates makes it difficult, if not impossible, to establish a consistent algorithm for r_s. However, the relatively good and consistent accuracy in ET_o when using a constant $r_s = 50\ \mathrm{s\ m^{-1}}$ during daytime gives good reason to recommend this value as a standardized parameter and coefficient for calculating ET_o. Based on a national study in the U.S. and studies by European and American researchers, the authors recommend that the FAO-PM ET_o method from FAO56, when applied on an hourly or shorter basis, use $r_s = 50\ \mathrm{s\ m^{-1}}$ for daytime and $r_s = 200\ \mathrm{s\ m^{-1}}$ for nighttime periods. This use will provide, on average, good agreement with computations made on a 24-h time step basis. No changes are suggested for the FAO-PM method for daily (24-h) time steps, where use of $r_s = 70\ \mathrm{s\ m^{-1}}$ should continue.

Keywords: Evapotranspiration; Standardization; Penman-Monteith; FAO; Reference evapotranspiration

1. Introduction

The FAO56 Penman-Monteith (FAO-PM) published by the Food and Agriculture Organization in Irrigation and Drainage Paper No. 56 (Allen et al., 1998) has received favorable acceptance and application over much of the world, including the United States, for establishing a reference evapotranspiration (ET_o) index as a function of weather parameters. The majority of applications of the FAO-PM method have been made with weather data summarized and reported for 24-h periods, so that the calculation time steps have typically been on a 24-h basis. With the increased development and installation of networks of electronic weather stations around the world, weather data are becoming increasingly available for calculation of ET_o on an hourly basis. There has been question and debate as well as studies on the appropriate expression and parameterization for the surface resistance (r_s) parameter of the PM equation and the associated coefficient for the reduced form FAO-PM equation when applied hourly. Currently, FAO56 (Allen et al., 1998) recommends using the same r_s value ($70\ \mathrm{s\ m^{-1}}$) for hourly time steps as is used for 24-h time steps.

The 24-h calculation time step has proven to be relatively consistent and accurate for estimating ET_o (Doorenbos and Pruitt, 1977; Jensen et al., 1990) and many lysimeter based studies have used the 24-h time step as a basis for calibration or verification of ET_o methods, including the FAO-PM (Allen et al., 1989; Steduto et al., 1996; Ventura et al., 1999; Todorovic, 1999; Howell et al., 2000; Berengena and Gavilán, 2005). The ASCE-EWRI (2005) have used the ASCE-PM equation and associated component equations (Jensen et al., 1990) on a 24-h calculation time step as the basis for a recent study and development for standardization of reference ET calculation in the U.S.A. (Itenfisu et al., 2003). The ASCE-PM component equations served as a primary basis for the FAO-PM (Smith et al., 1991). The favorable performance of the PM equation in many studies, when applied with 24-h (and even monthly) time steps, is somewhat surprising, since the formulation of the combination equation (combined energy balance and aerodynamic components) theoretically requires weather inputs on a nearly instantaneous basis. The general consistency and accuracy of the PM method for 24-h time steps speaks to the combination equation's robustness in estimating evaporative behavior given a particular set of meteorological conditions.

Several recent studies have shown that r_s for daytime hourly periods is less than 70 s m^{-1} in the FAO-PM for the standardized height of 0.12 m for clipped grass, and that lower values for r_s provide better agreement with ET_o measurements (Allen et al., 1996; Ventura et al., 1999; Todorovic, 1999; Wright et al., 2000; Steduto et al., 2003). Some recent studies (Ventura et al., 1999; Itenfisu et al., 2003; ASCE-EWRI, 2005; Irmak et al., 2005) have shown better agreement between summed hourly ET_o and ET_o computed on a 24-h time step when hourly ET_o uses a lower value for r_s than that used for the 24-h time step. This paper summarizes these and other findings and makes a recommendation to use the equivalent of 50 s m^{-1} for r_s for hourly periods during daytime and 200 s m^{-1} for r_s for hourly periods during nighttime. The use of $r_s = 70$ s m^{-1} is still considered to be a reasonable, reliable, and desirable constant for 24-h calculation time steps for the standardization of ET_o with sufficiently good accuracy to serve as a standardized reference and evaporative index (Allen and Fisher, 1990; Ventura et al., 1999; Todorovic, 1999; Lecina et al., 2003; ASCE-EWRI, 2005). Pereira et al. (1999) reviewed the concept of reference ET and relations to crop coefficients, including advantages of tall and short references.

The recommendation to use $r_s = 50$ s m^{-1} for hourly time steps during daytime and 200 s m^{-1} for hourly time steps during nighttime is intended to provide a standardization over the short-term for hourly calculation of ET_o that is congruent with FAO56 as applied with 24-h time steps. The recommendation is not intended to replace research simulation models and other applications that contain direct applications of the PM equation or other multi-layer approaches.

2. The FAO-Penman-Monteith equation

The "full-form" Penman-Monteith (PM) equation can be expressed as:

$$\mathrm{ET} = \frac{\Delta(R_n - G) + \rho_a c_p (e_s - e_a)/r_a}{\left(\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)\right)\rho_w \lambda} \tag{1}$$

where ET is the evapotranspirative flux expressed as depth per unit time, Δ the slope of the saturation vapor pressure versus temperature curve, R_n the net radiation flux density at the surface, G the sensible heat flux density from the surface to the soil (positive if the soil is warming), ρ_a the air density, c_p the specific heat of moist air at constant pressure, e_s the saturation vapor pressure at air temperature, e_a the actual vapor pressure of the air, r_a the aerodynamic resistance to turbulent heat and/or vapor transfer from the surface to some z height above the surface, γ the pyschrometric constant, r_s the bulk surface resistance that describes the resistance to flow of water vapor from inside the leaf, vegetation canopy or soil to outside the surface, ρ_w the density of liquid water, and λ is the latent heat of vaporization. All parameter units in (1) must cancel so that the remaining units for ET are presented as L t^{-1}, for example, mm h^{-1} or mm day^{-1}.

The full-form PM can be applied to a variety of vegetation conditions, including systems having varying leaf area and varying height. Some standardized parameterizations of the equation, including aerodynamic resistance, are described for application to grass reference ET_o in Allen et al. (1989), Jensen et al. (1990), Allen et al. (1994), Allen et al. (1998) and ASCE-EWRI (2005). When the supporting parameter equations for r_a, ρ_a, and λ are reduced and combined into the PM equation, the FAO styled "reduced form" equation results that has also been adopted by ASCE-EWRI (2005):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{C_n}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \tag{2}$$

where ET_o is in mm day^{-1} for 24-h time steps and mm h^{-1} for hourly time steps, R_n and G in MJ m^{-2} day^{-1} or MJ m^{-2} h^{-1}, T mean daily or hourly air temperature (°C), u_2 mean daily or hourly wind speed at 2-m height (m s^{-1}), e_s and e_a in kPa, Δ and γ in kPa °C^{-1}, and C_n and C_d are coefficients that differ with calculation time step, reference type (either grass ET_o or alfalfa ET_r in the application of ASCE-EWRI, 2005), and in some cases, with time of day. Units for C_n is K mm s^3 mg^{-1} day^{-1} or K mm s^3 mg^{-1} h^{-1} and units for C_d is s m^{-1}.

Values for C_n and C_d are presented in Table 1 for the FAO-PM and standardized ASCE-PM equations. For the FAO-PM, a grass reference ET_o is calculated and C_n = 900 for 24-h

Table 1
Values for C_n and C_d in Eq. (2) for the FAO-PM and ASCE-EWRI standardized PM equations (as reported in Allen et al., 1998 and ASCE-EWRI (2005))

Method	Calculation time step	C_n	C_d
FAO-PM (ET_o)	24-h	900	0.34[c]
	Hourly-proposed	37	0.24/0.96[a]
ASCE-PM (ET_o)	24-h	900	0.34
	Hourly	37	0.24/0.96[a]
ASCE-PM (ET_r)[b]	24-h	1600	0.38
	Hourly	66	0.25/1.7[a]

[a] The first value is for daytime periods (when $R_n > 0$) and the second value is for nighttime.
[b] ET_r is reference ET from 0.5 m tall alfalfa.
[c] The C_d = 0.34 is now recommended to be changed to 0.24 for daytime and 0.96 for nighttime for hourly or shorter time steps.

and $C_n = 37$ for hourly time steps. These values are characteristic of 0.12 m tall grass. Parameter $C_d = 0.34$ in Allen et al. (1998) for all time steps for FAO-PM, representing $r_s = 70$ s m^{-1}. Eq. (2) is also employed in the ASCE-EWRI (2005) standardization of ET$_o$, where similar to FAO-PM, the standardized short reference, representing cool season grass clipped to 0.12 m height, uses $C_n = 900$ for 24-h and $C_n = 37$ for hourly time steps (Table 1). The ASCE-EWRI standardization deviates from FAO-PM in the value for C_d, where $C_d = 0.24$ for hourly time steps during daytime (defined as when $R_n > 0$) and $C_d = 0.96$ for hourly time steps during nighttime. The 0.24 and 0.96 values for C_d for hourly applications stem from the use of $r_s = 50$ s m^{-1} during daytime and $r_s = 200$ s m^{-1} during nighttime, rather than assuming $r_s = 70$ s m^{-1} for hourly time periods. For 24-h calculation time steps, ASCE-PM uses 70 s m^{-1}, which is the same as for FAO-PM and standardized calculations of all parameters in the equation (for R_n, G, e_s, e_a, Δ, and γ) are identical to FAO-PM (ASCE-EWRI, 2005). In addition to application of (2) for the grass reference, ASCE-EWRI (2005) provided values for C_n and C_d for application to a standardized alfalfa reference ET (Table 1). In both FAO56 and ASCE-EWRI applications of the PM for 24-h calculation time steps, e_s is calculated as the average of saturation vapor pressure at daily maximum and at daily minimum air temperature.

3. Traditional parameterization of surface resistance for reference surfaces

Surface resistance r_s in the PM represents the coupled effect of resistance to vapor flow through leaf stomates and within soil to the soil surface. r_s also contains some effects of resistance to vapor flow within the canopy structure (Alves et al., 1998; Alves and Pereira, 2000). For a wet (saturated) surface, r_s is by definition essentially zero and (1) reverts to a form similar to the original Penman equation. Surface resistance for densely growing vegetation has often been computed in the PM as a function of effective leaf area by assuming that all leaves function as resistors in parallel:

$$r_s = \frac{r_l}{\mathrm{LAI_{eff}}} \tag{3}$$

where r_l is a bulk stomatal (or surface) resistance of the vegetation per unit leaf area (LAI) (s m^{-1}) and LAI$_{\mathrm{eff}}$ is the effective leaf area index involved, on average, in energy exchange, and thus contributing to ET. Parameter r_l is the inverse of the stomatal conductance per unit leaf area. Several earlier studies have fixed the value of r_l at 100 s m^{-1} for well-watered agricultural crops (Monteith, 1965; Szeicz and Long, 1969; Allen et al., 1989) when calculations were made on a 24-h basis. However, it is recognized that r_l varies during the course of a day with levels of solar radiation, leaf temperature, and vapor pressure gradient (Jarvis, 1976; Stewart, 1989; Price and Black, 1989) and r_l increases with environmental stresses such as soil moisture deficit (Stewart, 1988; Stewart and Verma, 1992; Hatfield and Allen, 1996).

A standardized estimation for LAI$_{\mathrm{eff}}$ was suggested for the dense grass and alfalfa reference crops by Allen et al. (1989), Jensen et al. (1990), Allen et al. (1994), and ASCE-EWRI (2005) based on Szeicz and Long (1969) as:

$$\mathrm{LAI_{eff}} = 0.5\,\mathrm{LAI} \tag{4}$$

The 0.5 multiplier suggests that only half (the upper part) of a dense canopy is active in heat and vapor transport and is the zone of major net radiation absorption (Szeicz and Long, 1969; Choudhury and Idso, 1985). Ben-Mehrez et al. (1992) suggested an expression for $\mathrm{LAI_{eff}}$ that predicts a larger ratio for $\mathrm{LAI_{eff}}$/LAI at small LAI and smaller ratio when LAI is large:

$$\mathrm{LAI_{eff}} = \frac{\mathrm{LAI}}{0.3\,\mathrm{LAI} + 1.2} \tag{5}$$

Eq. (5) was based on data from Shuttleworth (1991) and Rochette et al. (1991) for semidense agricultural crops and predicts $\mathrm{LAI_{eff}} = 0.67$ LAI at LAI = 1, $\mathrm{LAI_{eff}} = 0.4$–0.5 LAI at LAI's between 3 and 4, and $\mathrm{LAI_{eff}} = 0.24$ LAI at LAI = 10. The equation is in general agreement with (4) for the standardized grass and alfalfa references, which have LAI of 3 and 4.5 (ASCE-EWRI, 2005).

3.1. A constant or variable surface resistance

In reality, r_s changes with time of day and with time of year. With 24-h time steps, r_s represents an equivalent daily surface resistance that has some bias associated with the impact of time-variation in solar radiation R_s, $e_s - e_a$, and wind speed during the day on measured $\mathrm{ET_o}$ over the 24-h period as well as with total day length. Algorithms to modify 24-h and hourly values for r_s as functions of various environmental parameters can be applied, but r_s has generally been fixed for purposes of predicting the climatic index $\mathrm{ET_o}$ to fosters standardization, consistency, and simplicity. Jarvis (1976), Beven (1979), Stewart (1989), Price and Black (1989), Rana and Katerji (1998), Alves et al. (1998), Perrier and Tuzet (1998), Alves and Pereira (2000), and Berengena and Gavilán (2005) provide structure and basis for environmentally deriving the value for r_s. Todorovic (1999) introduced a climatic based model to predict canopy resistance as a primary function of vapor pressure deficit (VPD), similar to previous approaches by Katerji and Perrier (1983), Rana et al. (1994), and Rana and Katerji (1998). Although elegant in structure and didactic in derivation, the "climatic" or "equilibrium" resistance models of Katerji, Rana and Todorovic suffer from the implicit, fundamental requirement that the surface for which r_s is being predicted must have the same or nearly the same characteristics as the surface responsible for forming the magnitude of VPD. In other words, the vegetation for which ET is predicted should be similar with regard to the value for r_s associated with the mean vegetation of the region. This requirement comes about from the implicit feedback relation assumed between r_s and VPD, and works reasonably well in rain-fed agriculture. However, it can fail under irrigated conditions in semiarid to arid regions, where VPD over irrigated fields contains some "history" or "memory" stemming from the characteristically higher VPD of the nonirrigated region, even when the near surface boundary layer has come into "equilibrium" with the irrigated surface. Therefore, the direct, causal and predictive relation between VPD and r_s of an underlying irrigated surface breaks down. The Todorovic model also suffers from the assumption that the canopy resistance from a nonsaturated surface is the same for flow of both vapor and heat, whereas in reality, canopy resistance for vapor flow is a strong function of stomatal control, of which there is no counterpart in heat flow. The regional–local feedback problems associated with the Katerji and Todorovic models were noted by Pereira et al. (1999) and precluded Lecina et al. (2003) from obtaining accurate, consistent prediction of r_s over a range of weather conditions and locations.

For hourly time steps, one should anticipate that r_l will, at times reduce below the 100 s m^{-1} value commonly used for 24-h periods to values of 70–80 s m^{-1} or even lower. The reduction is caused by stomatal opening that tends to maximize under full-sunlight and with increasing temperature. This assumes that stability corrections are made or that buoyancy conditions are nearly neutral, which is often the case for the reference surface (Allen et al., 1996), and that vapor pressure deficit during daytime is not so large as to have a compensating negative effect on stomatal opening. Several studies have investigated the trend in r_l or r_s during daytime (Monteith, 1965; Stewart, 1989; Price and Black, 1989; Allen et al., 1996; Steduto and Hsiao, 1998a; Todorovic, 1999; Alves and Pereira, 2000; Lecina et al., 2003). Beven (1979), Rana and Katerji (1998) and Steduto and Hsiao (1998a,b) demonstrated the sensitivity of surface resistance to different heights of crops and water status. The bulk of these studies have indicated that the value for ET calculated from the PM equation has low enough sensitivity to the value for r_l or r_s, that the use of a constant value is warranted, especially for the reference surface, which by definition, has constant leaf area and soil water availability. In Fig. 4, Monteith (1965) shows relatively constant values for r_s during the day over unstressed grass.

4. Surface resistance in the FAO-PM method for daily calculation time steps

FAO56 recommends the use of 70 s m^{-1} for r_s for 24-h calculation time steps based on $r_l = 100$ s m^{-1} and LAI effectiveness of 0.5. With 24-h time steps, all energy sources and processes are characterized in bulk (i.e., solar radiation is reported as a bulk or average for the day, and wind speed and vapor pressure are averages for the day, and are used essentially as bulk quantities in the aerodynamic parameters and terms). Thus, one should expect that the 24-h value for effective r_s carries some bias and correction associated with the use of bulk terms for a 24-h period and some impact of daylength relative to nightlength. The 24-h value for r_s implicitly incorporates some of the behavior and variation in r_s within the 24-h period. The 24-h value $r_s = 70$ s m^{-1} has been found to provide a relatively accurate index of grass reference ET$_o$ over a relatively wide range of sites, as summarized in Table 2, and is still recommended for standardized ET$_o$ calculation for 24-h time steps.

5. Emperical evidence for using a reduced hourly surface resistance in the FAO-PM method

Smith et al. (1991) and the FAO56 publication recommended the use of $r_s = 70$ s m^{-1} for hourly time periods based on some comparisons in the Western U.S. and Europe and for consistency with applications on 24-h time steps. Other studies; however, have suggested that r_s for daytime should be lower than 70 s m^{-1} for the standardized ET$_o$ calculation and are needed to produce summed estimates of daily ET$_o$ that are equivalent to values produced

Table 2
Locations where the FAO-PM method applied daily and, using the equivalent of $r_s = 70$ s m^{-1} for vegetation height $h = 0.12$ m for 24-h (daily) calculation time steps, has produced reliable prediction of ET_o (within 5% of measurements on average)

Location	Climate	Source
Davis	Mediterranean	Allen et al. (1989), Jensen et al. (1990)
Lompoc	Mediterranean	
Seabrook	Subhumid	
South Park	Semiarid	
Copenhagen	Subhumid	
Logan, UT	Semiarid	Allen and Fisher (1990)
Policoro, Italy (after quality control of solar radiation data)	Mediterranean	Todorovic (1999)
Bushland, TX	Semiarid	Howell et al. (2000)
Crossville	Subhumid	Odhiambo et al. (2001)
Bushland	Semiarid	
Paraipaba	Semiarid	
Zaragoza, Spain	Semiarid	Lecina et al. (2003)
Córdoba, Spain	Semiarid	Lecina et al. (2003), Berengena and Gavilán (2005)
El Belen, Choquenaira, Patacamaya, and Oruro, Bolivia	Semiarid and subhumid	Garcia et al. (2004)

using a 24-h calculation time step (Lecina et al., 2003; Itenfisu et al., 2003; Irmak et al., 2005). Allen et al. (1996) found a daytime value of $r_s = 50$ s m^{-1} for LAI = 3 to perform well against precision lysimeter measurements at Davis, CA and Logan, UT as illustrated later. Ventura et al. (1999) found $r_s = 42$ s m^{-1} performed best against hourly grass ET_o measurements at Davis when G was computed as $G = 0.1R_n$ during daytime as standardized in FAO56. Todorovic (1999) found $r_s \sim 50$ s m^{-1} to best fit the clipped ryegrass ET_o grown in the Davis lysimeter during the early 1960's (Pruitt and Lourence, 1985). Wright et al. (2000) found $r_s = 30$–50 s m^{-1} to best predict ET from lush, erect clipped tall fescue grass grown in the Kimberly precision lysimeter. Lecina et al. (2003) gave indication that $r_s \sim 50$ s m^{-1} would improve agreement between hourly ET_o predicted by the FAO56 PM method and lysimeter measurements at Zaragoza, Spain. Berengena and Gavilán (2005) found the FAO56 PM method, using calculated R_n and $r_s \sim 50$ s m^{-1}, predicted within 2% of lysimeter measurements of ET from clipped cool season grass at Cordoba, Spain on hourly time steps. Steduto and Hsiao (1998b) reported canopy resistance of full-grown and well-watered maize (LAI > 5) that was always less than 50 s m^{-1}, as measured by the Bowen-Ratio Energy-Balance method. Although on a different crop, this result adds to the experimental evidence in support of $r_s < 70$ s m^{-1} during daytime.

5.1. Neglection of stability correction under reference conditions

Instability of the equilibrium boundary layer, caused by large fluxes of sensible heat at the surface that induce buoyancy, can have large influence on the transport of heat and vapor flow, and consequently the calculation for r_a (Brutsaert, 1982). Correction to the aerodynamic resistance term in Eq. (1) is often made for stability correction (SC) during estimation of evapotranspiration, especially where the sensible heat flux component is large, for example, over dry or sparse vegetation. There is some question whether SC is necessary when calculating reference ET. In most instances, under reference conditions, sensible heat flux is small enough, relative to ET and available energy, that energy and vapor transfer are not strongly affected by buoyancy. Under these conditions, corrections required for boundary layer instability or stability are relatively small and can be ignored with little error.

As an illustration of small SC for reference conditions, Fig. 1a and b show the full-form ASCE-PM Eq. (1) applied to half-hour calculation time steps for ET, performed with and

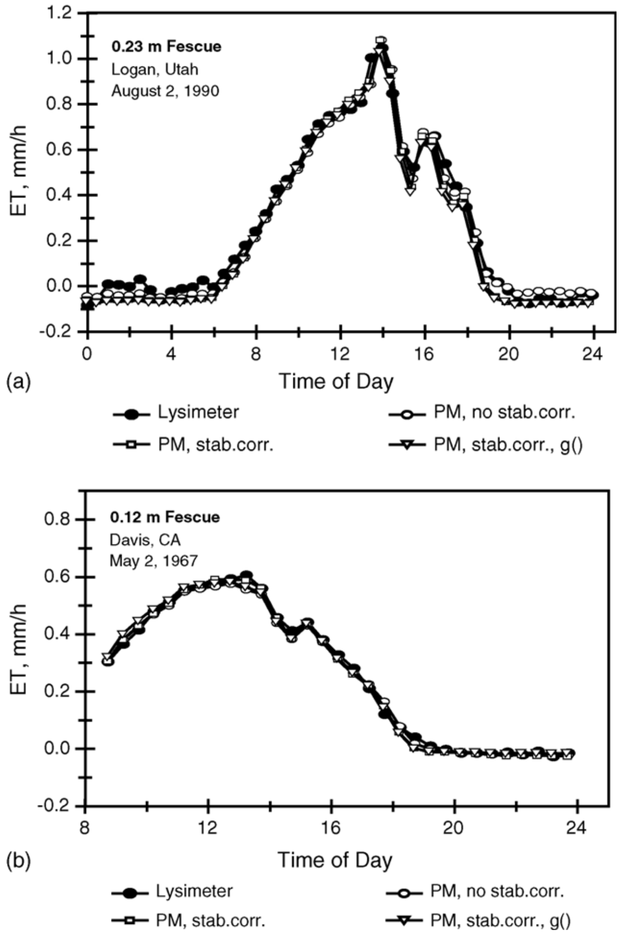

Fig. 1. Comparisons between measured ET and ET estimated using the PM equation with and without integrated stability correction with using two estimating procedures for r_s at (a) Logan, Utah and (b) Davis, CA (after Allen et al., 1996).

without SC on individual days (identified as ''PM, stab. corr.'' and ''PM, no stab. corr.'') at Logan, UT and Davis, CA with comparison to lysimeter measurements. These data sets were used by Allen et al. (1996) to illustrate impacts of various types of SC, and more information on the applications is reported there, including the calculation of r_a. The SC used in Fig. 1 was based on integrated stability correction functions by Paulson (1970) and Webb (1970), as summarized in Brutsaert (1982) and Allen et al. (1996). Aerodynamic roughness was computed according to measured grass height. Bulk surface resistance, r_s, for the two data sets was estimated using (3), with $r_l = 75$ s m^{-1} and with LAI$_{eff}$ calculated using (4). Measurement or estimation of other parameters and lysimeter data are described in Allen et al. (1996).

As illustrated in Fig. 1, ET calculations were influenced little by inclusion of stability corrections at either location, even though values for the Monin-Obukhov z/L numbers (the reader is referred to Brutsaert, 1982; Allen et al., 1996) ranged from -0.5 to over 2 at Logan and -0.7 to 0.1 at Davis. The relatively low influence of SC for the reference ET estimates stems from the impact of the evaporating surface on reducing instability. Another reason stems from the presence of $1/r_a$ in both the numerator and in the denominator of the PM equation, so that a major amount of change in $1/r_a$ due to stability correction is self-cancelling, depending on the relative magnitudes of $R_n - G$, $e_s - e_a$, and r_s. The dips in calculated and measured ET during midafternoon periods at both locations were due to cloud passage, which reduced R_n and T. Impacts of stability correction would be greater for nonreference (i.e., dry) ET conditions.

The grass at Logan was clipped fescue grown as forage and with height (h) = 0.23 m on August 2, 1990. The LAI was estimated to be 5.5 m^2 m^{-2}. The grass at Davis was alta fescue clipped as turf with h = 0.12 m and measured LAI = 2.94 m^2 m^{-2}on May 2–3, 1967. R_n was calculated at Logan from measured R_s using the standard procedures from FAO56 and R_n at Davis was an average of measurements by three net radiometers (W.O. Pruitt, 1994, personal communication to R. Allen). The weather data were collected over a grass surface. The 1 m × 1 m × 1 m weighing lysimeter system at Logan had about 0.05 mm resolution on measurements (Allen and Fisher, 1990) and the resolution of the 6.1 m diameter round weighing lysimeter system at Davis was less than 0.02 mm resolution (Pruitt and Lourence, 1985).

5.2. *Use of stomatal conductance functions under reference conditions*

Two procedures were applied to estimate r_l used to calculate r_s for ET in the two data sets illustrated in Fig. 1. In the first procedure, where results are labeled ''PM, no stab. corr.'' and ''PM, stab. corr.,'' a constant value $r_l = 75$ s m^{-1} was applied to all time periods and r_s was estimated using (3). In the second procedure, labeled ''PM, stab. corr., g( ),'' a value for minimum leaf resistance, $r_{l_{min}} = 40$ s m^{-1} was used in conjunction with environmentally based conductance functions for reducing r_l. The conductance functions were based on Stewart (1989) and Price and Black (1989) as described in Allen et al. (1996). In the first procedure, the resulting values for r_s were 27 s m^{-1} at Logan and 50 s m^{-1} at Davis, the differences caused by differences in LAI and grass height. If adjusted to an equivalent r_s commensurate with 0.12 m height, in proportion to height of grass, the r_s at Logan becomes 50 s m^{-1}. In the second procedure, the minimum value for r_s

(=$r_{l_{min}}$/LAI$_{eff}$), before adjustment with the environmental functions, was 14 and 27 s m^{-1} at Logan and Davis, respectively, again due to differences in LAI. The environmental functions increased the values for r_s in the second procedure from 14 to 35 s m^{-1} during afternoon hours at Logan (where grass height was 0.23 m) and from 27 s m^{-1} to about 50 s m^{-1} at Davis. Surface resistance during nighttime hours ($R_n < 0$) was set equal to 200 s m^{-1} to approximate r_s for damp soil beneath the grass canopies (Allen et al., 1996) and for general agreement with lysimeter measurements.

The impact of using the environmental functions in conjunction with a minimum value for r_l was to largely produce the r_s = 50 s m^{-1} value (for h = 0.12 m) for most hourly periods during daytime. Therefore, the effect on estimated ET was similar to using a constant r_s = 50 s m^{-1} for h = 0.12 m. Both methods for r_l provided good comparison between estimated ET and ET measured by lysimeter. It is recognized that all locations will not respond in the same way as Logan and Davis and that 1 day at two locations is not sufficient to conclude behavior of stability correction and r_s. However, the two applications do illustrate the behavior that can be expected under reference conditions.

6. Performance of the Penman-Monteith method and r_s behavior at additional locations

A series of hourly ET for single or multiple days is presented in Figs. 2–5 for precision weighing lysimeter systems at Logan, UT, Davis, CA, Kimberly, ID, Badajoz, Spain, and Córdoba, Spain. These locations are classified as semiarid and/or Mediterranean. The intent of the figures is to illustrate the potential for relatively good and consistent behavior of the PM equation, using FAO56 parameterizations, when r_s = 50 s m^{-1} equivalent for h = 0.12 m is used rather than 70 s m^{-1} for hourly or shorter time steps. ET based on both r_s values (50 and 70 s m^{-1}) is shown in the figures. All calculations followed guidelines of Allen et al. (1998) and adopted by ASCE-EWRI (2005). The r_s = 70 s m^{-1} was applied to all hourly periods, including nighttime, as was originally suggested in FAO56, whereas the r_s = 50 s m^{-1} value was applied during daytime (when $R_n > 0$) and r_s = 200 s m^{-1} was applied during nighttime. The values for r_s were adjusted when h was not 0.12 m by dividing 50 or 70 s m^{-1} by the ratio of actual h to 0.12 m. This adjustment is consistent with the estimation of LAI in FAO56 and ASCE-EWRI (2005) for clipped grass, where LAI = 0.24 h.

The plots in Figs. 2–5 show residual values for r_s, smoothed over periods of three hours, computed by inverting the PM equation using lysimeter values as the known ET, and using no stability correction. The residual r_s values were adjusted to a common grass height basis of 0.12 m using adjustment inversely proportional to h. For the day shown for Logan (Fig. 2a), the residual r_s had very low values (less than 25 s m^{-1}) during morning hours (values not shown prior to 09:00 were nearly zero or even negative due to the impact of lysimeter measured ET exceeding that predicted by the PM equation even with r_s = 0). Some of this effect may have been caused by a thermal bias in the lysimeter measurement system (Allen and Fisher, 1990). The r_s at midday (adjusted to a value equivalent to h = 0.12 m) averaged about 50 s m^{-1} and the average for the values shown (09:00–17:00) was 46 s m^{-1}. The residual r_s at Davis for the day shown in Fig. 2b followed the

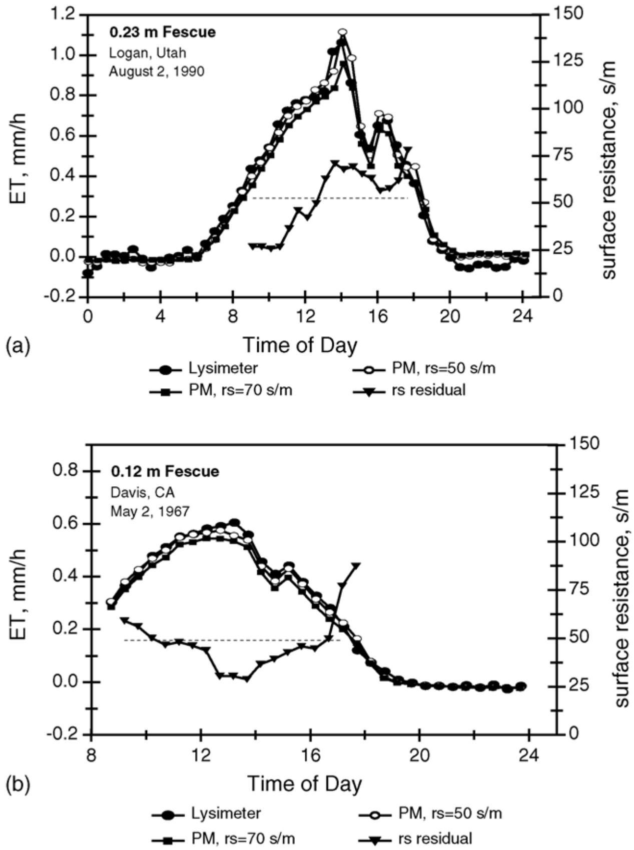

Fig. 2. Comparisons between measured ET and ET estimated using $r_s = 50$ and 70 s m^{-1} at (a) Logan, UT and (b) Davis, CA (Davis data from W.O. Pruitt, University California, personal communication) (horizontal dashed line represents $r_s = 50$ s m^{-1}).

characteristic shape generally expected for r_s, where lowest values (~30 s m^{-1}) occurred for a few hours during midday, and where r_s increased with time distance from midday. The averaged r_s for the values shown for Davis (09:00–17:00) was 49 s m^{-1}. At both sites, the use of constant $r_s = 50$ s m^{-1} agreed well with lysimeter measurements during nearly all daytime hours, especially when compared to the PM equation applied using $r_s = 70$ s m^{-1} (also shown in the figures).

Fig. 3a–c shows comparisons of hourly ET by a clipped tall fescue measured by lysimeter at Kimberly, ID for 3 days in May, 1988. The approximately 2 m × 2 m × 1.5 m lysimeter at Kimberly had resolution of about 0.02 mm. The computed ET_o was by the Penman-Monteith equation using the equivalent of $r_s = 50$ s m^{-1} for a clipped height of 0.12 m, but adjusted in inverse proportion to h when h deviated from 0.12. The grass heights for the 3 days were 0.12, 0.17, and 0.12 m on May 11, 15, and 27. R_n was estimated from R_s using the FAO56 and ASCE-EWRI (2005) guidelines and G was calculated as a function of R_n using the same guidelines.

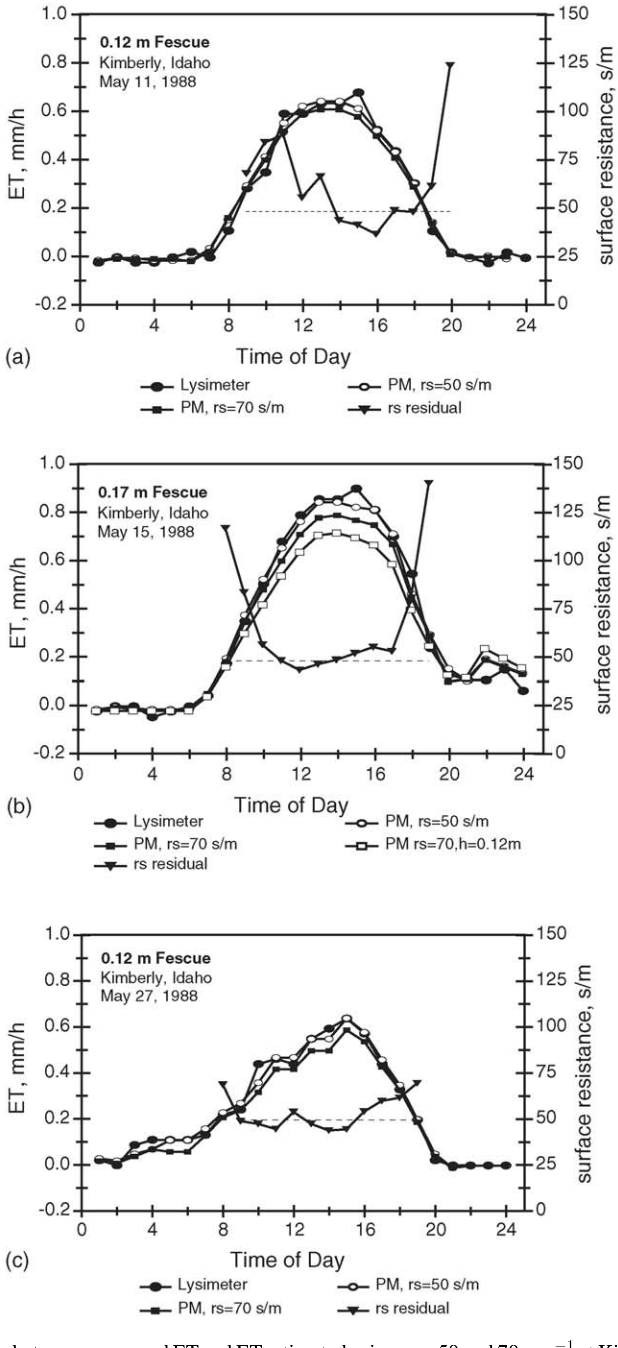

Fig. 3. Comparisons between measured ET and ET estimated using $r_s = 50$ and $70\ \mathrm{s\ m^{-1}}$ at Kimberly, Idaho on (a) May 11, 1988 (b) May 15, 1988 and (c) May 27, 1988 (data from J.L. Wright, USDA-ARS, personal communication) (horizontal dashed line represents $r_s = 50\ \mathrm{s\ m^{-1}}$).

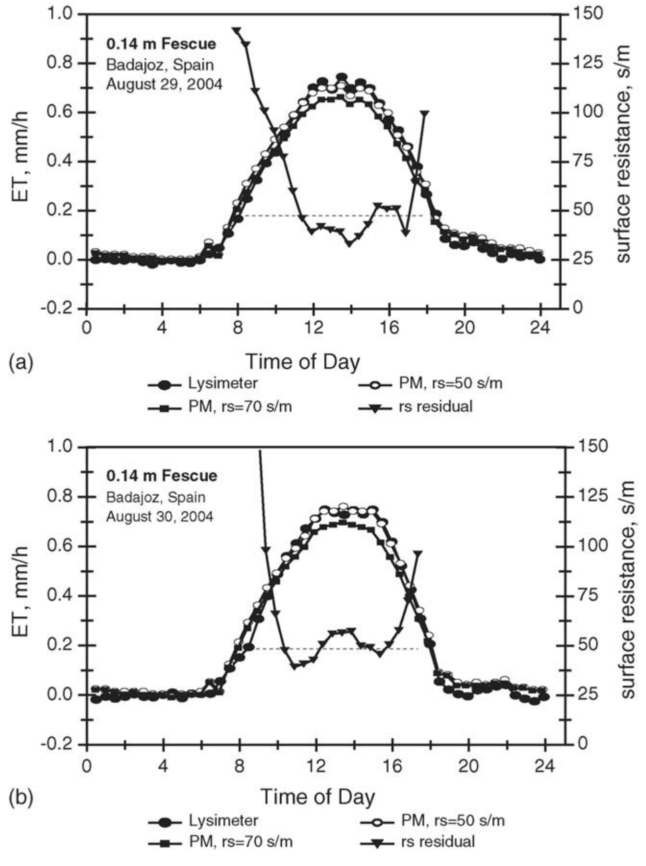

Fig. 4. Comparisons between measured ET and ET estimated using $r_s = 50$ and 70 s m^{-1} at Badajoz, Spain on (a) August 29, 2004 and (b) August 30, 2004 (data from J. Baselga Yrisarry, AYM, Junta Ex, Badajoz, Spain, personal communication) (horizontal dashed line represents $r_s = 50$ s m^{-1}).

Examination of the 3 days at Kimberly shows, similar to Logan and Davis, good agreement between the lysimeter measured ET and the ASCE-PM equation when applied with $r_s = 50$ s m^{-1} for $h = 0.12$ m (with adjustment to $50 \times 0.12/0.17 = 35$ s m^{-1} on May 15 for $h = 0.17$ m to simulate the actual lysimeter condition). ET_o estimated with $r_s = 70$ s m^{-1} underpredicted by a small amount for the 2 days having $h = 0.12$ m and by a larger amount for the day when $h = 0.17$ m (especially if h were held at 0.12 m in the calculations as illustrated by the additional curve "PM, $r_s = 70$, $h = 0.12$ m"). The trend in r_s (computed as a residual) exhibited some variation in trend shape among days, but tended to average about 50 s m^{-1} during daytime hours for all 3 days. The results suggest that $r_s = 50$ s m^{-1} at $h = 0.12$ m was a better predictor of lysimeter measurements at Kimberly than $r_s = 70$ s m^{-1} for hourly time periods. The comparisons at Kimberly also demonstrate the importance of comparing a standardized PM equation having fixed h and r_s parameters with lysimeter measurements only when the lysimeter vegetation exhibits similar characteristics (i.e., when $h \sim 0.12$ m).

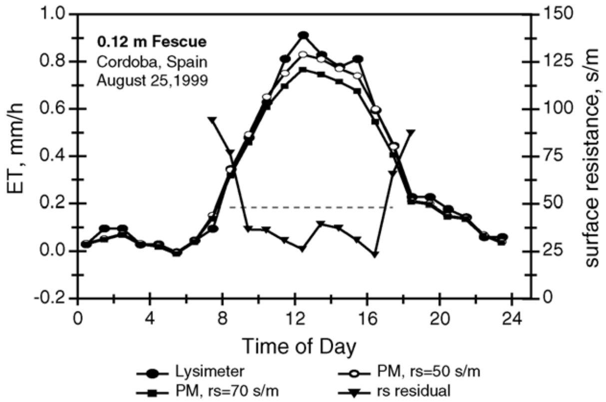

Fig. 5. Comparisons between measured ET and ET estimated using $r_s = 50$ and 70 s m^{-1} at Córdoba, Spain on August 25, 1999 (data from J. Berengena, CIFA Alameda del Obispo, Córdoba, Spain, personal communication) (horizontal dashed line represents $r_s = 50$ s m^{-1}).

Fig. 4 shows ET behavior for clipped fescue (Festuca arundinacea) during 2 days near Badajoz, Spain (latitude: 38.85°N; longitude: 6.66°W; elevation: 198 m). The lysimeter at Badajoz was 2.67 m × 2.25 m in surface area and 1.5 m depth (soil depth was 1.1 m) with resolution of about 0.02 mm. The computed ET_o was by the PM equation using the equivalent of $r_s = 50$ s m^{-1} for a clipped height of 0.12 m, but adjusted to 0.14 m height to fit the measured height for the 2 days in August. R_n was estimated from R_s using the guidelines in Jensen et al. (1990) and G was measured at 0.08 m depth and adjusted to the surface using measured soil temperature. The PM calculations that used $r_s = 50$ s m^{-1} equivalent fit measured ET well throughout the day, as compared to using $r_s = 70$ s m^{-1}, and computed residual r_s averaged close to 50 s m^{-1} for both days.

Fig. 5 shows a comparison between estimated and measured ET for a day at Córdoba, Spain within the Guadalquivir Valley (latitude: 37°51′N; longitude: 4°51′W; elevation: 110 m), noted for its advective climate and high ET_o (Berengena and Gavilán, 2005). The fescue grass (Festuca arundinacea) was 0.12 m height on August 25, 1999. The weighing lysimeter system has a 2 m × 3 m surface area and 1.5 m in depth and has resolution for hourly ET measurement of 11.3 W m^{-2}, equivalent to 0.02 mm h^{-1} of ET. Hourly ET was calculated as the average of 120 mass readings made at two second intervals within a four minute interval centered on the corresponding hour (Berengena and Gavilán, 2005). R_n was estimated from R_s using the FAO56 and ASCE-EWRI (2005) guidelines and G was calculated as a function of R_n using the same guidelines.

The PM equation with $r_s = 50$ s m^{-1} predicted relatively well for the August date at Córdoba, but underestimated measured ET by a small amount during midday (Fig. 5). The r_s computed as a residual averaged about 35 s m^{-1} during midday. Over a longer period, Berengena and Gavilán (2005) reported the PM method to predict within 2% of lysimeter measurements on hourly time steps when using calculated R_n and $r_s = 50$ s m^{-1}.

The results shown for the samples of hourly data from Logan, Davis, Kimberly, Badajoz and Córdoba, for fescue grass, indicate that $r_s = 50$ s m^{-1} at $h = 0.12$ m approximates ET as measured by lysimeter relatively well over a range of locations using the PM method as parameterized following FAO56 and ASCE-EWRI (2005). Results agree with findings by Ventura et al. (1999) and Todorovic (1999) that indicate the need to use an r_s that is less than 70 s m^{-1} for hourly time steps.

7. Sum-of-hour ET$_o$ calculations versus 24-h calculation time steps

ASCE-EWRI (2005) conducted a comprehensive comparison of major reference ET equations for ET$_o$ using weather data from 49 sites across the United States. The 16 states contributing data ranged from New York to California and from Florida to Washington, and represented diverse climates, ranging from humid to arid (Itenfisu et al., 2003). The ASCE-EWRI analysis is summarized here to show the relatively good and consistent performance from using r_s = 50 s m^{-1} for hourly calculations during daytime relative to 24-h time steps that use r_s = 70 s m^{-1}. A total of 76 site years were used to compare hourly to daily calculations. Site elevations ranged from 2 to 2895 m and mean annual precipitation ranged from 150 to 2030 mm. Mean ET$_o$ calculated by the ASCE-PM method for the peak month varied from 2.78 to 9.68 mm day^{-1}. Statistics were summarized for calendar years and growing seasons, which were generally defined as April–October for the northern climates.

A concerted effort was made by ASCE-EWRI to obtain high-quality agricultural weather data sets collected from weather station sites having sufficient "green" fetch and that were located over and adjacent to a surface of grass or other short vegetation. Although some of the sites approached the ideal for a reference ET station (well-watered clipped grass for a distance of 100 m in all directions), many of the sites had less than this amount of green fetch. In general, however, the vast majority of sites represented conditions expected in well-watered agricultural environments. Quality assurance and integrity assessment criteria, following the procedure described by Allen (1996), Allen et al. (1998) and ASCE-EWRI (2005), were applied to the weather data sets. These criteria included comparing measured solar radiation to theoretical solar radiation during clear sky periods and comparing daily average dew point temperature with minimum daily air temperature. Sites exhibiting significant deviation from quality control checks were excluded from the ET analyses.

Results of comparisons have been summarized by Itenfisu et al. (2003) and ASCE-EWRI (2005) and included comparisons between sum-of-hourly and daily values by the PM method using both r_s = 50 and 70 s m^{-1} for hourly time steps during daytime. ASCE-EWRI found that r_s = 50 s m^{-1} during daytime (defined as when $R_n > 0$) and r_s = 200 s m^{-1} for nighttime for hourly calculation time steps produced summed ET$_o$ over 24-h periods that best agreed with ET$_o$ computed using r_s = 70 s m^{-1} for daily (24-h) calculation time steps. Summary results for ratios are shown in Fig. 6 across the range of longitudes of the ASCE-EWRI study. Each point represents, for a specific location year combination, the ratio of the summed hourly ET$_o$ to 24-h calculation time step ET$_o$ over the growing season. Mean seasonal ET for each location and year by the hourly applications are plotted in Fig. 7 against the 24-h calculation. The summed hourly ET$_o$ using r_s = 50 s m^{-1} during daytime and r_s = 200 s m^{-1} for nighttime agrees very well with the 24-h calculations (based on r_s = 70 s m^{-1}) for nearly all locations. The PM application

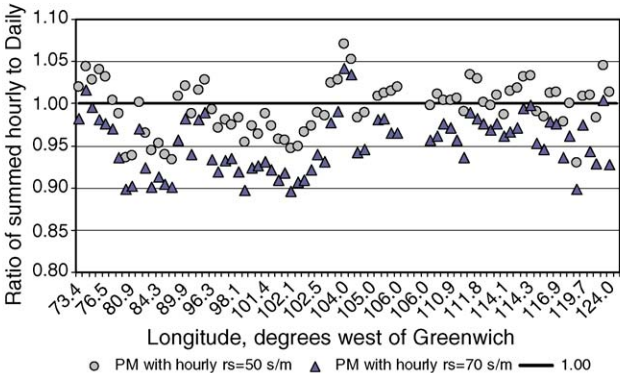

Fig. 6. Ratios of summed hourly ET_o over 24-h time steps to ET_o computed using 24-h time steps for growing seasons at 49 sites (generally 2 years per site) across the U.S.A., where hourly ET_o was computed using $r_s = 50$ s m^{-1} during daytime and $r_s = 200$ s m^{-1} during nighttime, or was computed using $r_s = 70$ s m^{-1} for all hourly time steps. Calculations for 24-h time steps were made using $r_s = 70$ s m^{-1} for both data sets.

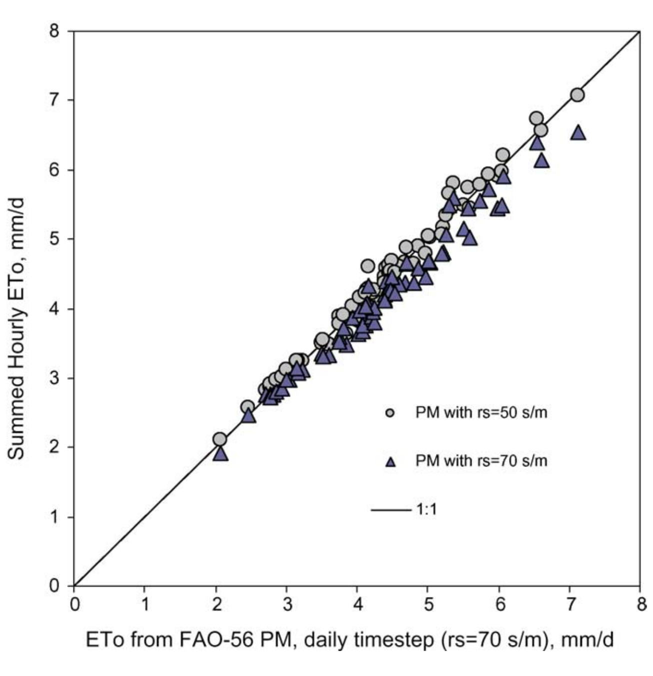

Fig. 7. Mean ET_o during the growing season computed by summing hourly calculations over 24-h periods vs. ET_o computed using 24-h time steps for growing periods at 49 sites (generally 2 years per site) across the U.S.A., where hourly ET_o was computed using $r_s = 50$ s m^{-1} during daytime and $r_s = 200$ s m^{-1} during nighttime, and using $r_s = 70$ s m^{-1} during all periods. Calculations for 24-h time steps were made using $r_s = 70$ s m^{-1} for both data sets.

Table 3
Statistical summary of the comparisons between various reference ET methods for growing season periods from 76 site years of hourly data from the ASCE-EWRI (2005)

Method	Ratio				RMSD (mm day^{-1})				RMSD as % of mean daily ET
	Maximum	Minimum	Mean	Standard deviation	Maximum	Minimum	Mean	Standard deviation	Mean
Sum-of-hourly ET_o using Eq. (2) vs. daily ET_o using Eq. (1) and $r_s = 70$ s m^{-1}									
Hourly $r_s = 70$ s m^{-1} all periods	1.04	0.90	0.95	0.034	0.89	0.20	0.39	0.15	8.9
Hourly $r_s = 50$ s m^{-1} daytime, 200 s m^{-1} nightime	1.08	0.94	1.01	0.029	0.68	0.24	0.36	0.09	8.0
Sum-of-hourly ET_o using Eq. (2) vs. daily ET_o using Eq. (2) and $r_s = 70$ s m^{-1}									
Hourly $r_s = 70$ s m^{-1} all periods	1.04	0.90	0.96	0.032	0.83	0.20	0.37	0.18	8.5
Hourly $r_s = 50$ s m^{-1} daytime, 200 s m^{-1} nightime	1.08	0.94	1.01	0.028	0.66	0.23	0.33	0.08	7.7

Maximum, minimum, mean, and standard deviations are based on site year means for growing periods. Ratio is the ratio of the sum-of-hourly ET_o using Eq. (2) to daily ET_o computed on a 24-h time step. RMSD is root mean square difference between the sum-of-hourly ET_o and 24-h time step ET_o.

using 70 s m^{-1} for hourly periods underestimated ET_o produced by the daily calculation time-step.

The PM application standardized by ASCE-EWRI (2005) is applied using calculations for all parameters (Δ, R_n, G, γ, λ, r_a, e_s, etc.) that are identical to those prescribed by FAO56. The ASCE-EWRI (2005) standardized PM equation for ET_o, is thus essentially identical to the FAO56 PM for 24-h and longer time steps, including the means for estimating R_n and G and the use of the simplified equation form expressed by (2). The ASCE standardization deviates from the current FAO56 (Allen et al., 1998) for hourly or shorter calculation time steps only in the values used for r_s. In addition, ASCE-EWRI (2005) has updated coefficients used to calculate clear sky solar radiation (R_{so}) and the procedure to determine R_n during nighttime periods.

Table 3 summarizes ratios over growing seasons for the same locations shown in Figs. 6 and 7 for the standardized PM form of Eq. (2) applied hourly for r_s = 70 s m^{-1} for all hourly periods (row 1) and for hourly r_s of 50 (daytime) and 200 s m^{-1} (nighttime) (row 2) relative to 24-h ET_o calculated on a 24-h time step using r_s = 70 s m^{-1}. All calculations were based on the full-form of the PM as expressed in Eq. (1). Details on the calculations are given in Itenfisu et al. (2003) and ASCE-EWRI (2005). Rows three and four in Table 3 show the same calculations, but where the basis for the 24-h time step is the simplified PM form (Eq. (2)). Comparison of statistics in rows 1 and 2 with those in rows 3 and 4 show that there is little loss of performance by using the simplified form of the PM Eq. (2) for either set of r_s values.

The ratios in Table 3 for the PM method applied using r_s = 70 s m^{-1} for hourly time steps ranged from 0.90 to 1.04 and averaged 0.95 over all locations, with a standard deviation in the ratios of 0.034. Ratios for the summed hourly PM application that used r_s = 50 s m^{-1} for daytime and r_s = 200 s m^{-1} for nighttime ranged from 0.94 to 1.08 and averaged 1.01 over all locations, with a standard deviation in ratios of 0.029. Root mean square differences (RMSD) between summed hourly and daily time steps are also summarized in Table 3. The RMSD is an index of expected absolute deviation between the summed hourly and daily time step ET_o values on any given day. The mean RMSD across all sites and growing seasons was about 0.3–0.4 mm day^{-1} for all methods or about 8% of mean daily ET_o.

The ASCE-EWRI (2005) study results indicate that the decision by ASCE-EWRI to use r_s = 50 s m^{-1} for daytime and r_s = 200 s m^{-1} for nighttime for hourly or shorter computations and to use r_s = 70 s m^{-1} for 24-h computational time steps in the standardized ASCE-PM method provides near equality between the summed hourly and 24-h computation time steps over growing seasons. The adoption of r_s = 50 s m^{-1} for daytime periods supports experimental findings illustrated in Figs. 2–5 and those reported by Ventura et al. (1999), Todorovic (1999), and Lecina et al. (2003). This adoption is now encouraged for standardized applications of the FAO-PM method (i.e., FAO56) for hourly time steps.

8. Summary and conclusions

Variability in hour to hour trends in r_s among locations and dates, as shown in Figs. 2–5, makes it difficult, if not impossible, to establish a consistent algorithm for matching or reproducing r_s trends at all locations. However, the relatively good and consistent accuracy in calculation of ET_o when using a constant, fixed value of $r_s = 50\ s\ m^{-1}$ during daytime gives good reason to recommend $r_s = 50\ s\ m^{-1}$ during daytime and $r_s = 200\ s\ m^{-1}$ during nighttime as a standardized procedure for calculating ET_o. Based on a national study in the U.S.A., and studies by European and American researchers, the authors recommend that the FAO-PM ET_o method from FAO56, when applied on an hourly or shorter basis, use $r_s = 50\ s\ m^{-1}$ for daytime and $r_s = 200\ s\ m^{-1}$ for nighttime periods. This use will provide, on average, best agreement with computations made on a 24-h time step basis. This usage agrees well with lysimeter measurements summarized and reviewed in this paper and elsewhere.

The use of $r_s = 50\ s\ m^{-1}$ for daytime and $r_s = 200\ s\ m^{-1}$ for nighttime periods for hourly application of the FAO56-PM will establish consistency with the U.S. national standardization efforts (ASCE-EWRI, 2005) and will benefit the transfer of crop coefficients among nations. The change in hourly r_s in the FAO-PM method is equivalent to the use of $C_n = 37$ in the numerator and $C_d = 0.24$ in the denominator in Eq. (2) for hourly time steps during daytime (defined as when $R_n > 0$) and $C_d = 0.96$ in the denominator for hourly time steps during nighttime. No changes are recommended for the FAO-PM method for daily (24-h) time steps, so that $C_n = 900$ and $C_d = 0.34$ for 24-h time steps.

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